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Performance of gears with WC/C coating

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ABSTRACT: In this study the performance of case hardened and WC/C coated helical gears were evaluated using a 160mm centre distance back-to-back gear performance test rig simulating wind turbine gearbox application. The surface contact life of WC/C coated gear pairs was compared with uncoated as-ground gear pairs, and at regular intervals during gear tests, the change of gear tooth profile were monitored. It was found that the coating of a gear surface led to much reduced loss of tooth profile as well as resulted in a change of failure mode from conventional micropitting and macropitting based fatigue to wear dominated failure processes.

1 GENERAL INSTRUCTIONS

Surface engineering of gears is becoming increasingly important in high power density mechanical power transmission applications. The growing use of modern clean steel for gear production has resulted in a reduction of traditional sub-surface initiated failure in preference for surface initiated failures in the form of micropitting, macropitting and scuffing (Design Unit, 2002). Control of these failure modes requires enhanced surface properties such as the application of coating.

Hard, thin, low processing temperature, low friction and high wear resistance are the common characteristics shared by coatings that have been successfully applied to gears. Among all coatings tested it was found that Physical Vapour Deposition (PVD) coatings are of the most suitable ones for case hardened gears such as those containing B_4C, DLC, CrN, NbCSN and WC/C. There is strong evidence to suggest that suitable gear coatings are able to eliminate micropitting and significantly improve gear surface durability (Anderson & Lev, 2003) (Krantz T. L., 2004) (Krantz, Cooper, Townsend, & Hansen , 2003) (Krzan, Kalin, & Vizintin, 2006) (Moorthy & Shaw, 2012) (Design Unit, 2015).

In general, however, there is lack of systematic research and mathematical modelling to help the understanding about how coating on gear surface works. The added complexities regarding gear mesh mechanism with a combination of sliding and rolling, often under heavy Hertzian stresses with the presence of lubricant, make it more so. This paper provides more findings about the positive influence that a WC/C coating has on gear performance.

2 TEST METHOD

Effects of WC/C coating on gear performance were studies by two comparative tests, with test conditions being set to be typical for wind turbine gearbox applications. The first test served as a baseline detecting the performance of un-coated gears in as-ground condition. In the second test, coated gears were run at the same condition.

Each gear test involved running two pairs of test gears with the same surface condition for a prolonged period of time at a constant shaft rotation speed of 3000rpm on the pinion, a torque of 4500Nm on the wheel and a maintained oil inlet temperature of 90°C. In the process of a gear test, the rig was stopped at every 8 million cycles of running to allow inspections to be carried out on test gears. In order to build a record of progression of gear surface degradation such as micropitting or wear with the increase of running cycles, at each interval test gears were removed from the test rig and re-measured using a Gear Measurement Instrument (GMI) to quantify profile loss. This routines was only completed until the accumulated running cycles reached 48 million.

2.1 *Test rig*

The rig used to carry out gear testing was a Design Unit 160 mm centre distance back-to-back gear performance test rig (Figure 1). The rig works on a mechanical power recirculation principle with two identical gearboxes ("A" and "B") sitting at each end of a long test bed connected with two torsionally compliant shaft systems. The torque is generated by a hydraulic torque actuator and maintained through a computerised close-loop control algorithm in the range of between 0 to 6000Nm. The rotation speed of test gears is adjustable as the rig is powered by an inverter-fed induction motor through a pulley. The lubrication oil temperature is regulated by the use of electric heaters and water-cooled heat exchangers. The running of test gears started from "zero" torque, followed by a programmed running-in procedure involving ramping up rotation speed and torque stepwisely, until the steady test condition has been reached with all essential test parameters i.e. rotation speed, torque and oil temperature being under close control.

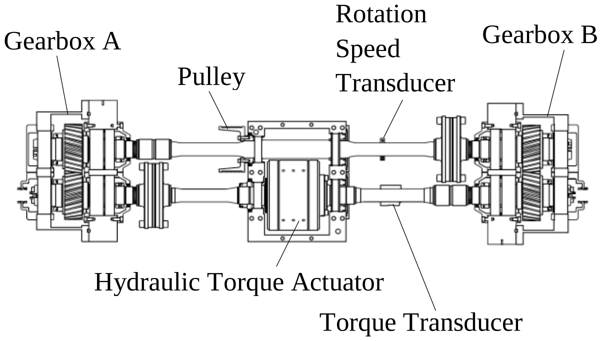

Figure 1. Illustration of a Design Unit 160mm centre distance back-to-back gear performance test rig.

2.2 *Test gear*

Test gear pairs were 6mm module, 28.1° helix, 44mm facewidth, with 23 teeth for pinions and 24 teeth for wheels. Test gear were made of case carburising alloy steel 18CrNiMo7-6, case carburised, direct quenched and tempered to surface hardness of 700-750 Hv. The metallurgic quality was characterised and deemed to comply with ISO 6336-5:2003. All gears were form ground using a vitreous grinding wheel to achieve an accuracy grade 5 according to ISO 1328-1:2013, and a Ra flank surface roughness of 0.40 – 0.50 µm complying with ISO 4287:1997. Test gears were tip relieved and crowned in order to simulate realistic wind turbine gearbox applications. There were 4 pairs of test gears used for this investigation. 2 pairs in as-ground condition were used to generate baseline data while another 2 pairs were coated and tested comparatively.

2.3 *Coating*

The PVD coating applied to gear teeth in as-ground condition was a WC/C based, thus a mixture of metal and diamond-like carbon. The coating was designed to provide reduced adhesive wear. According to the coating service provider, the hardness of the coating is believed to be 8-12 GPa and the coefficient of friction (dry) vs. steel 0.1 – 0.2. By sectioning coated gear teeth the thickness of coating was found to be 2-3µm by light microscopy inspection (Figure 2). After the application of coating slight drop of surface hardness (less than 50Hv) was found but no significant of change of microstructure was observed. It can be seen with the aid of a focus variation microscope that after coating gear tooth flank surfaces were smoothed up (Figure 3).

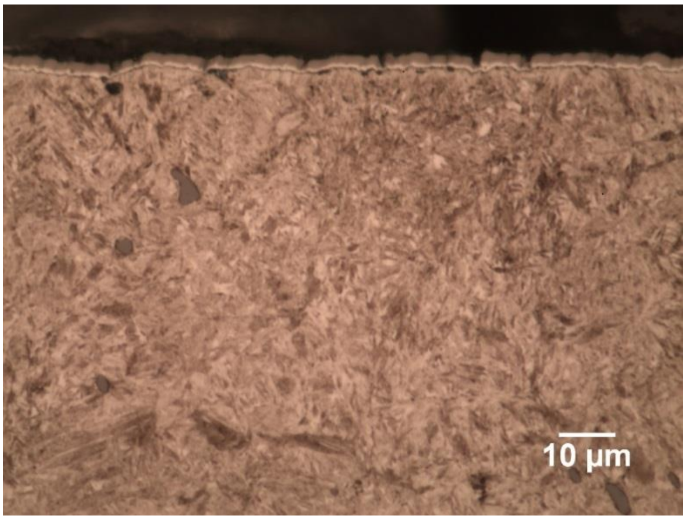

Figure 2. Light microscope image revealing section of gear tooth and the coating on top (nital etched). The thickness of the coating is 2-3µm.

2.4 *Oil and Temperature*

A mineral based extreme pressure heavy duty gear lubricant was used. This oil is intended for highly loaded enclosed gears and bearings with a 40°C / 100°C viscosity of 320 / 25 mm^2/s. The inlet temperature of the lubrication oil was set and maintained as 90°C.

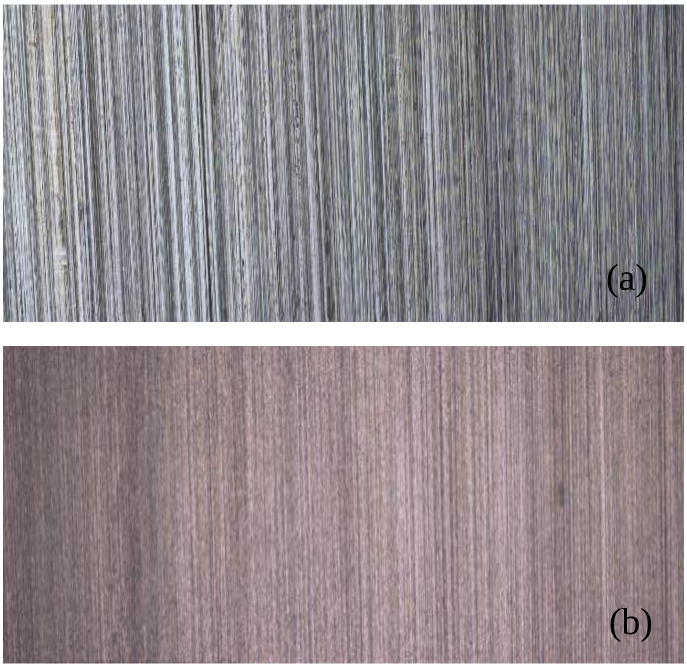

Figure 3. Images generated by a 3D focus variation optical instrument revealing the surface texture change from as ground (a) to WC/C coated (b) gear flank surfaces (image size: 4.64mm × 1.62mm).

3 RESULTS AND DISCUSSIONS

The averaged loss of gear profile, quantified at test intervals using a GMI, is shown in Figure 4. Each value shown in the vertical axis is the averaged loss of gear profile at mid facewidth position of every tooth of all 4 test gears involved in each test (two gearboxes each containing two gears). Loss of profile of coated gears were normalised against baseline gears in as-ground condition. It was obvious that coating gear tooth flank surfaces with WC/C has resulted in much reduced loss of tooth profile, this trend became more like so especially in the range of longer running cycles which exceeded 24 million cycles.

The flank surfaces of as-ground gears were found to degrade continuously with the increase of running cycles. Measurable micropitting appeared after the first 8 million cycles of running, it is believed that micropitting have started earlier and found to be progressive, which has caused increased loss of gear's involute profile. Macropitting was found appearing at the edge of micropitted area once the profile loss has reached a critical level as shown in Figure 5.

The flank surface of WC/C coated gears were found to be largely intact at the end of gear testing i.e. after 48 million running cycles. A photo of typical appearance of a gear tooth surface at the end of gear testing is shown in Figure 6. It was observed that coated gear flank surfaces have been run in fairly quickly, believed to be within the first 8 million cycles, and after that coated surfaces have remained un-changed for the rest of the test. Although it was found that coating has been removed especially at the dedendum of a gear but this material removal only limited to the thickness of the coating itself. Surface fatigue phenomenon that would normally appear on the as-ground gear tooth surface such as micropitting and macropitting (Figure 5) did not occur at all.

The mechanism of improved gear performance as a result of coating both gears with WC/C is not understood but believe to be involving a non-fatigue, however wear-like process. Much more is needed to do in order to fully understand the interference between coated surfaces, coated surface and lubricant, as well as the influence of coating debris carried by the lubrication oil.

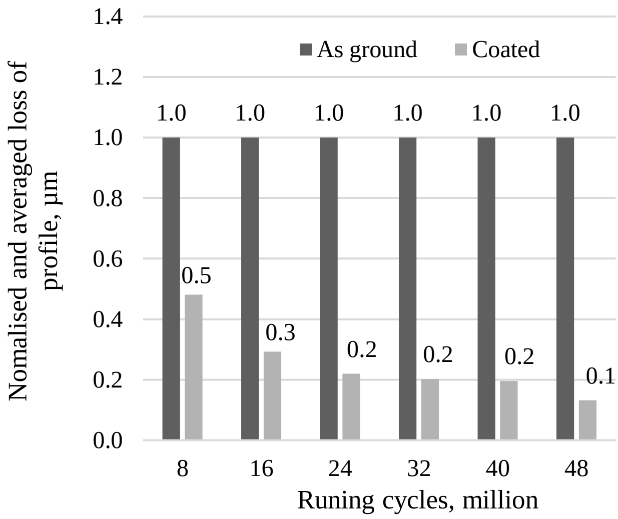

Figure 4. A comparison between as ground gear and coated gears regarding loss of gear profile vs. running cycles.

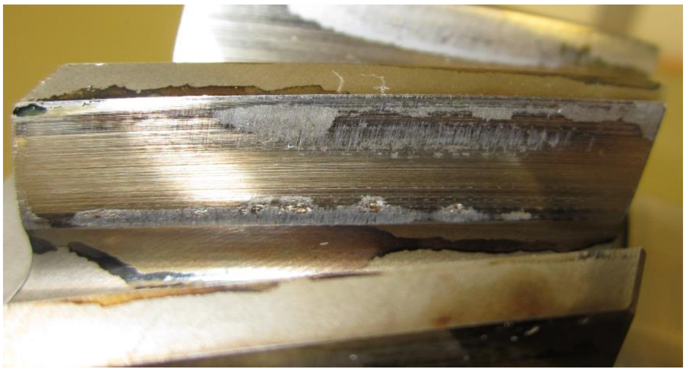

Figure 5. Photo showing typical surface degradation of an as-ground test gear after its being run for 48 million cycles. Gear flank surface is seen to be populated with micropitting and macropitting.

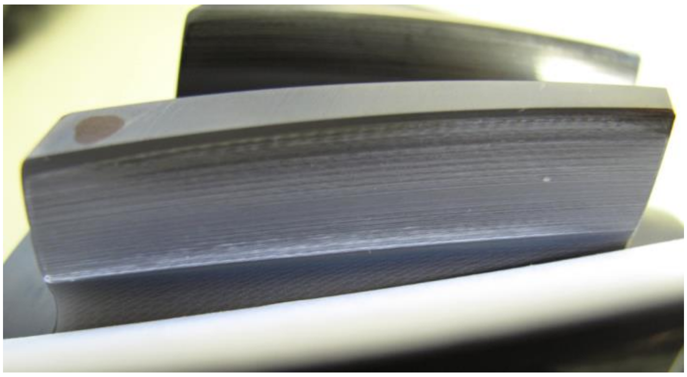

Figure 6. Photo showing typical surface condition of a WC/C coated test gear after it has been run for 48 million cycles at the same test conditions as that for as-ground gears. Gear flank surface is seen to have only minor wear.

4 CONCLUSIONS

Coating a pair of case hardened gears after grinding with WC/C results in much reduced loss of profile that would normally be significant in as-ground condition due to progressive micropitting and macropitting.

Compared with conventional case hardened gears in as-ground surface condition, additional WC/C coating leads to the change of gear surface contact failure mode from fatigue to wear related.

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